US 20010052893A1

(19) United States

(12) **Patent Application Publication** (10) **Pub. No.: US 2001/0052893 A1**

Jolly et al. (43) **Pub. Date: Dec. 20, 2001**

(54) **MAGNETICALLY-CONTROLLABLE, SEMI-ACTIVE HAPTIC INTERFACE SYSTEM AND APPARATUS**

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(21) Appl. No.: **09/922,322**

(22) Filed: **Aug. 3, 2001**

Related U.S. Application Data

(63) Continuation-in-part of application No. 09/189,487, filed on Nov. 10, 1998.

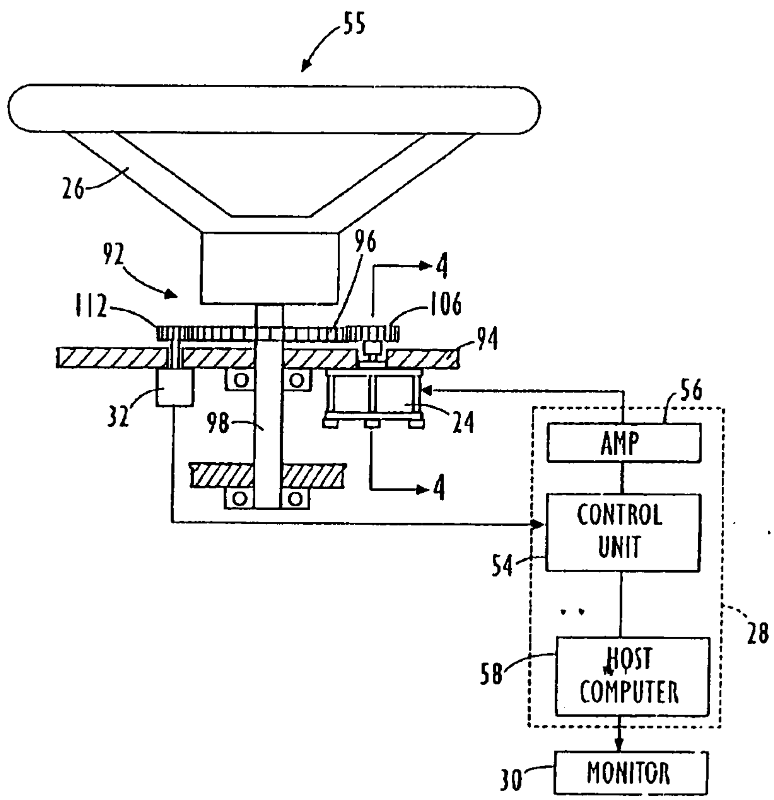
Publication Classification

(51) **Int. Cl.[7]** **G09G 5/00**

(52) **U.S. Cl.** **345/156**

(57) **ABSTRACT**

A haptic interface system or force feedback system having a magnetically-controllable device that provides resistance forces opposing movement. The magnetically-controllable device is adapted for use with a force feedback computer system to provide force feedback sensations to the system's operator. The magnetically-controllable device contains a magnetically-controllable medium beneficially providing variable resistance forces in proportion to the strength of an applied magnetic field. The system further comprises a controller that executes an interactive program or event, a video display, and a haptic interface device (e.g. joystick, steering wheel) in operable contact with an operator for controlling inputs and responses to the interactive program. Based on the received inputs and on processing the program, the controller provides a variable output signal, corresponding to a feedback force, to control the magnetically-controllable device for providing dissipative resistance forces to oppose the movement of the haptic interface device and to provide the operator with a force feedback sensation.



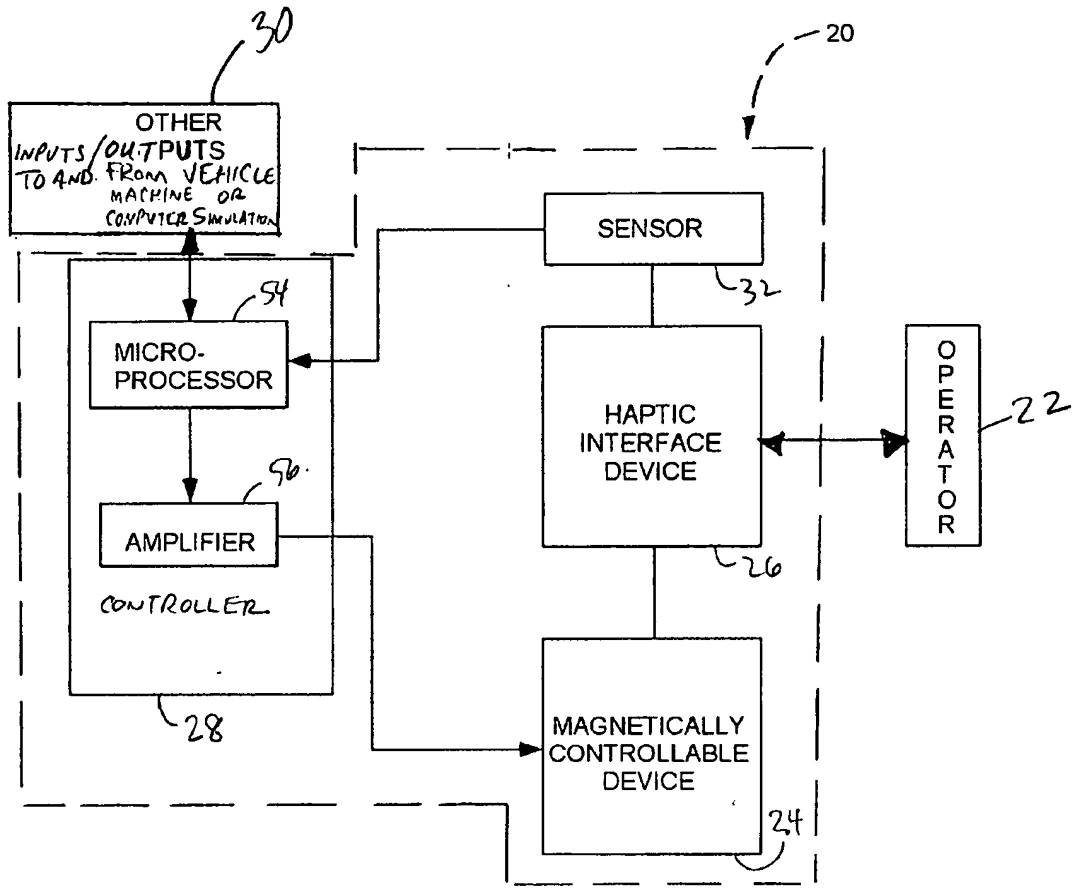

30
20
OTHER
INPUTS/OUTPUTS
TO AND FROM VEHICLE
MACHINE OR
COMPUTER SIMULATION
SENSOR
32
54
MICRO-
PROCESSOR
HAPTIC
INTERFACE
DEVICE
OPERATOR
22
56
AMPLIFIER
26
CONTROLLER
28
MAGNETICALLY
CONTROLLABLE
DEVICE
24

FIG. 1A

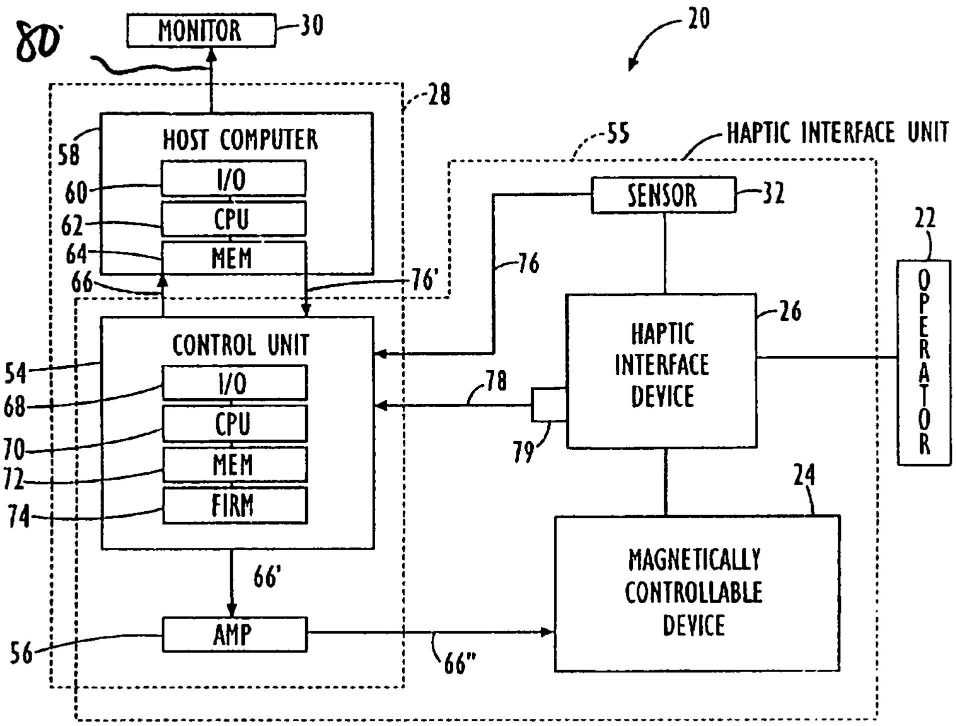


FIG. 1B

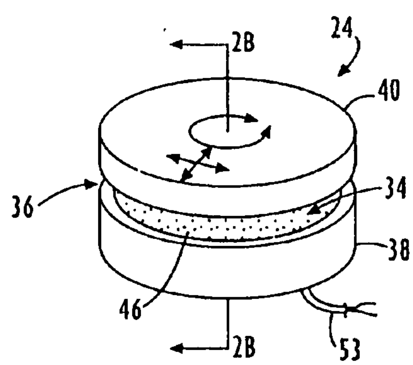


FIG. 2A.

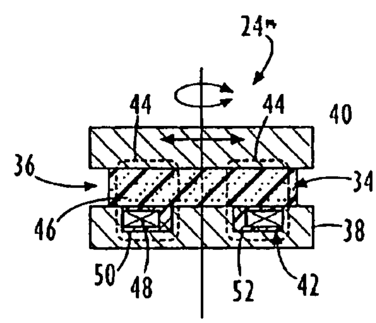


FIG. 2B.

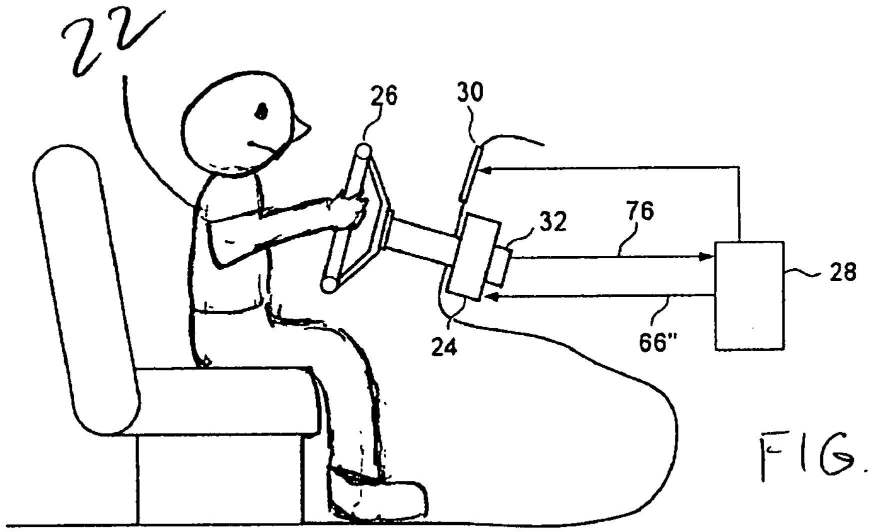


FIG. 1C

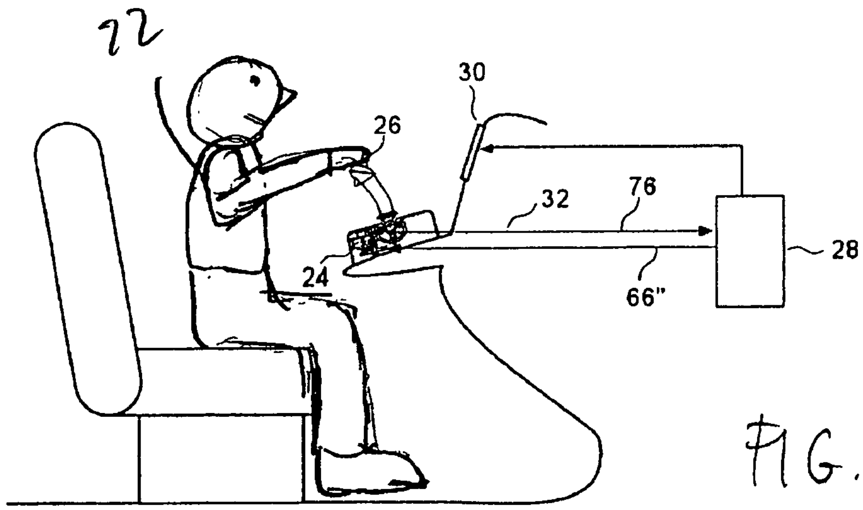


FIG. 1D.

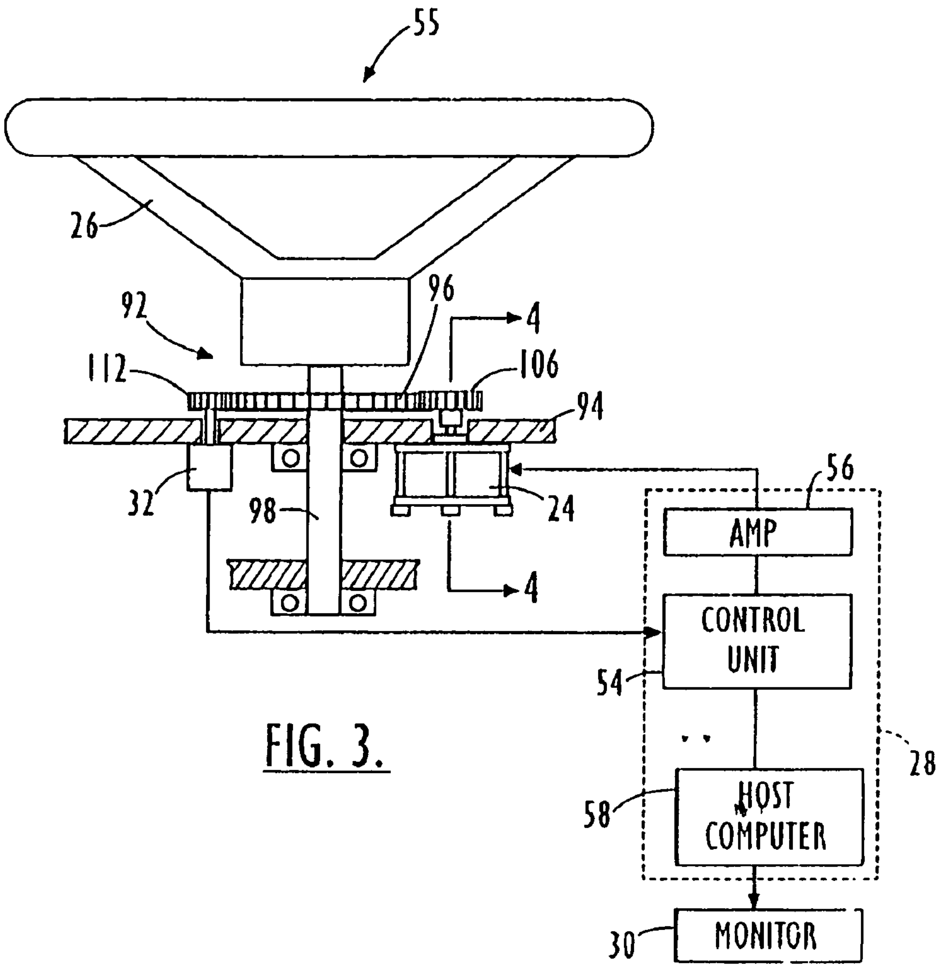

55
26
92
96
4
112
106
94
56
32
98
24
AMP
4
CONTROL UNIT
54
28
58
HOST COMPUTER
30
MONITOR

FIG. 3.

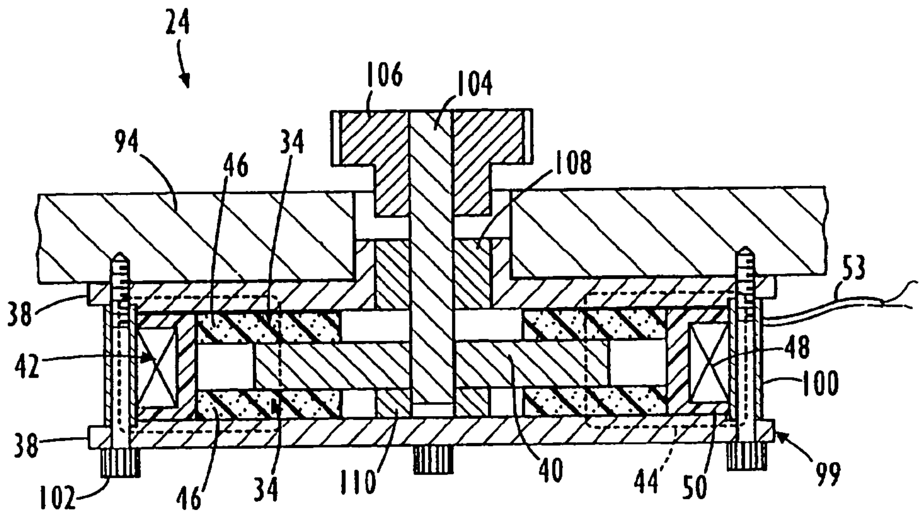

24
106
104
94
46
34
108
53
38
42
48
100
38
102
46
34
110
40
44
50
99

FIG. 4a.

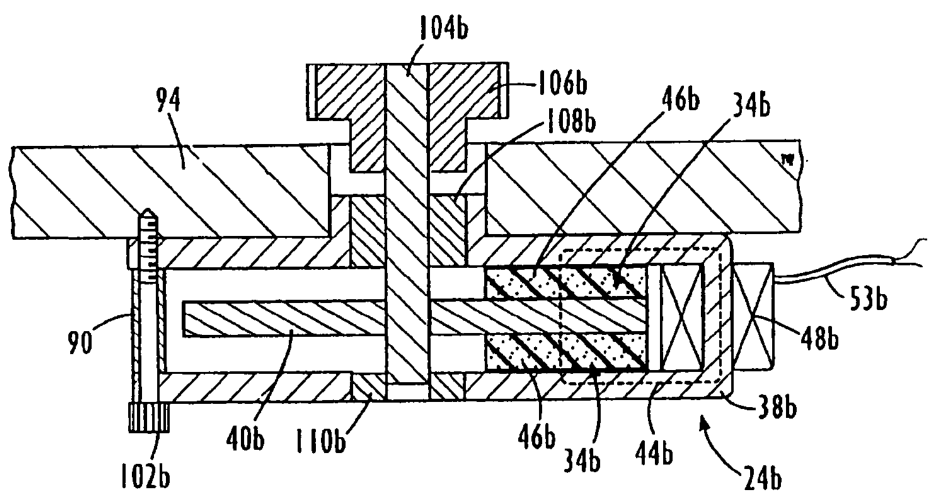

104b
94
106b
46b
34b
108b
53b
90
48b
38b
102b
40b
110b
46b
34b
44b
24b

FIG. 4b.

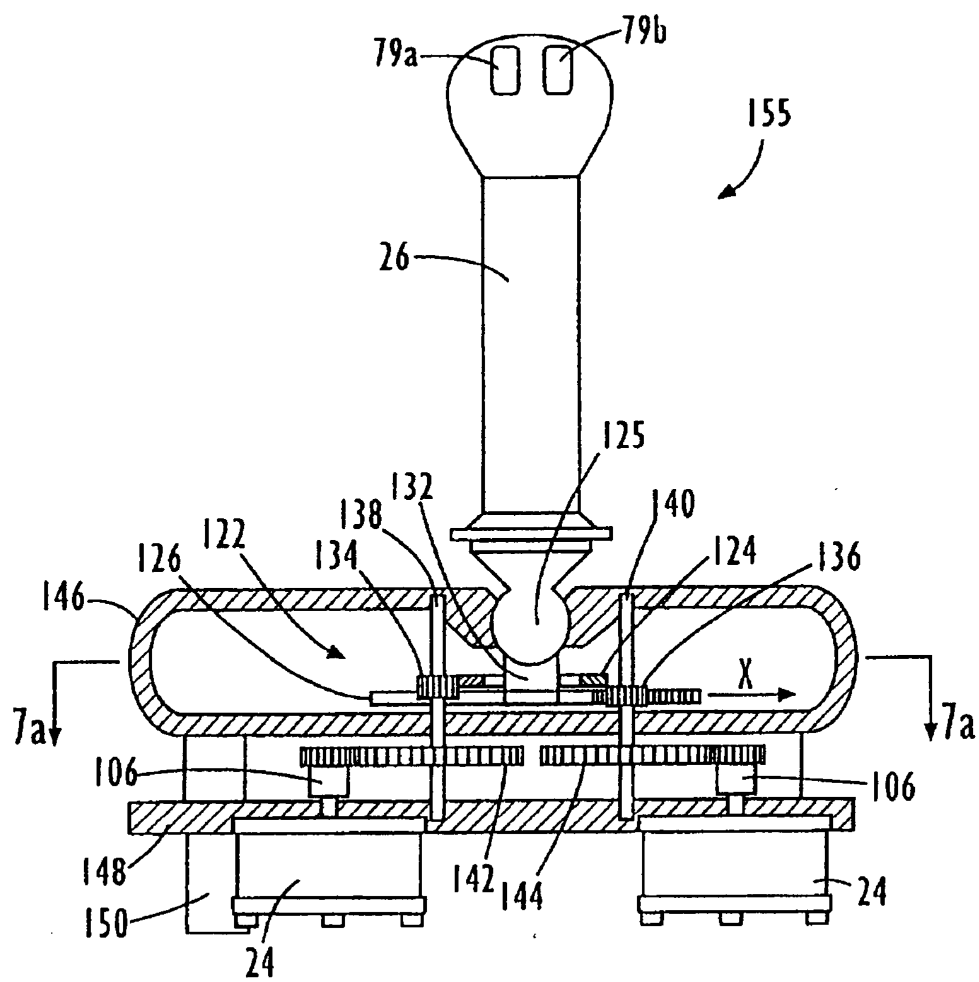
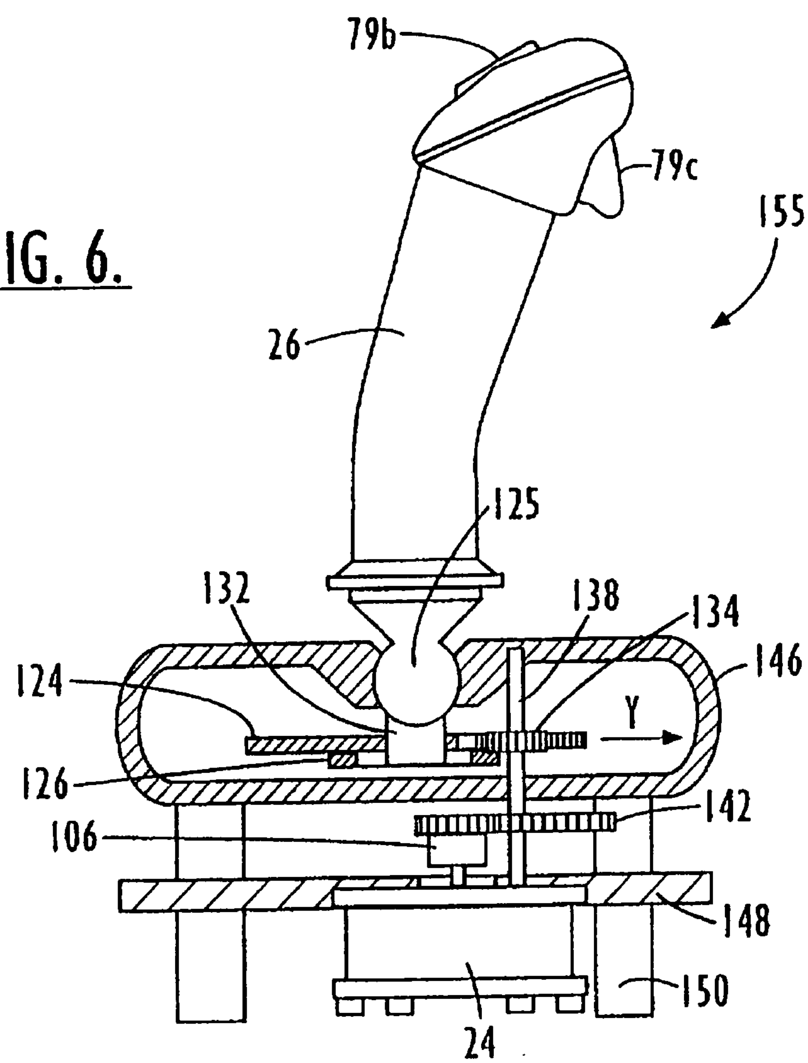

79a
79b
155
26
125
132
138
140
134
124
136
122
126
146
X
7a
7a
106
106
148
142
144
24
150
24

FIG. 5.

FIG. 6.



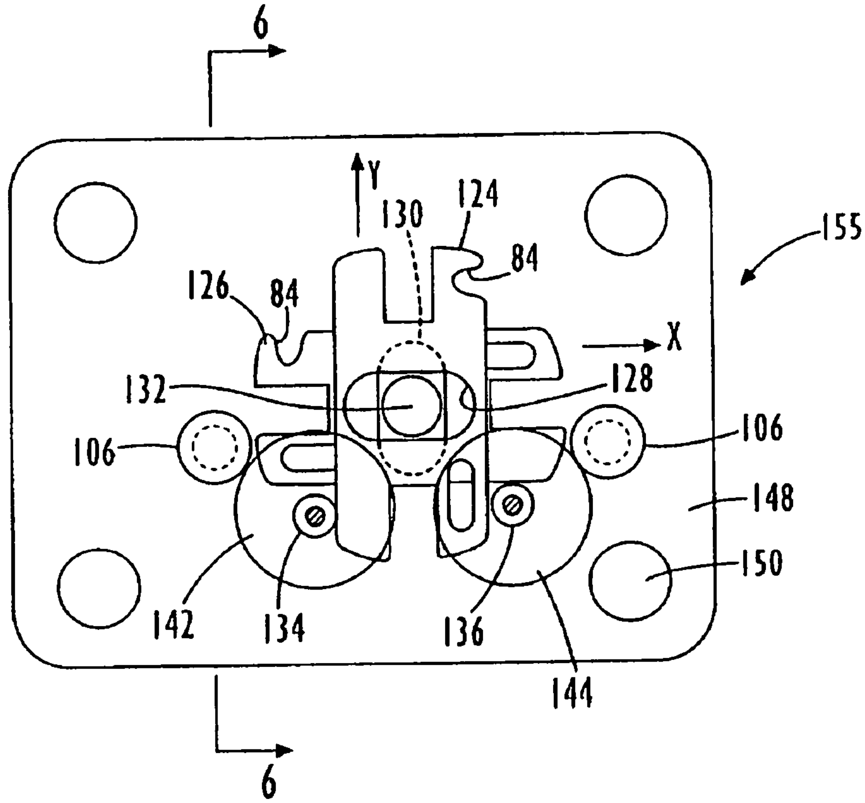

6
Y
130
124
155
84
126
84
X
132
128
106
106
148
150
142
134
136
144
6

FIG. 7a.

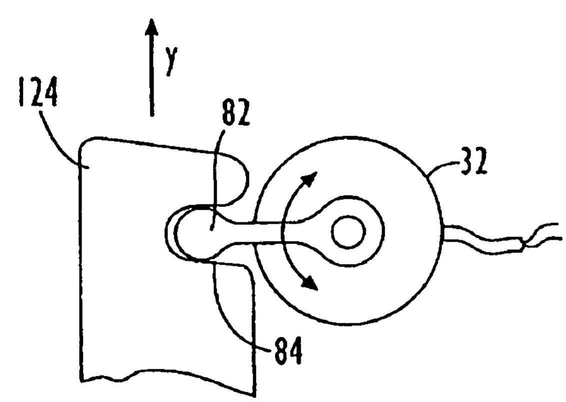

Y
124
82
32
84

FIG. 7b.

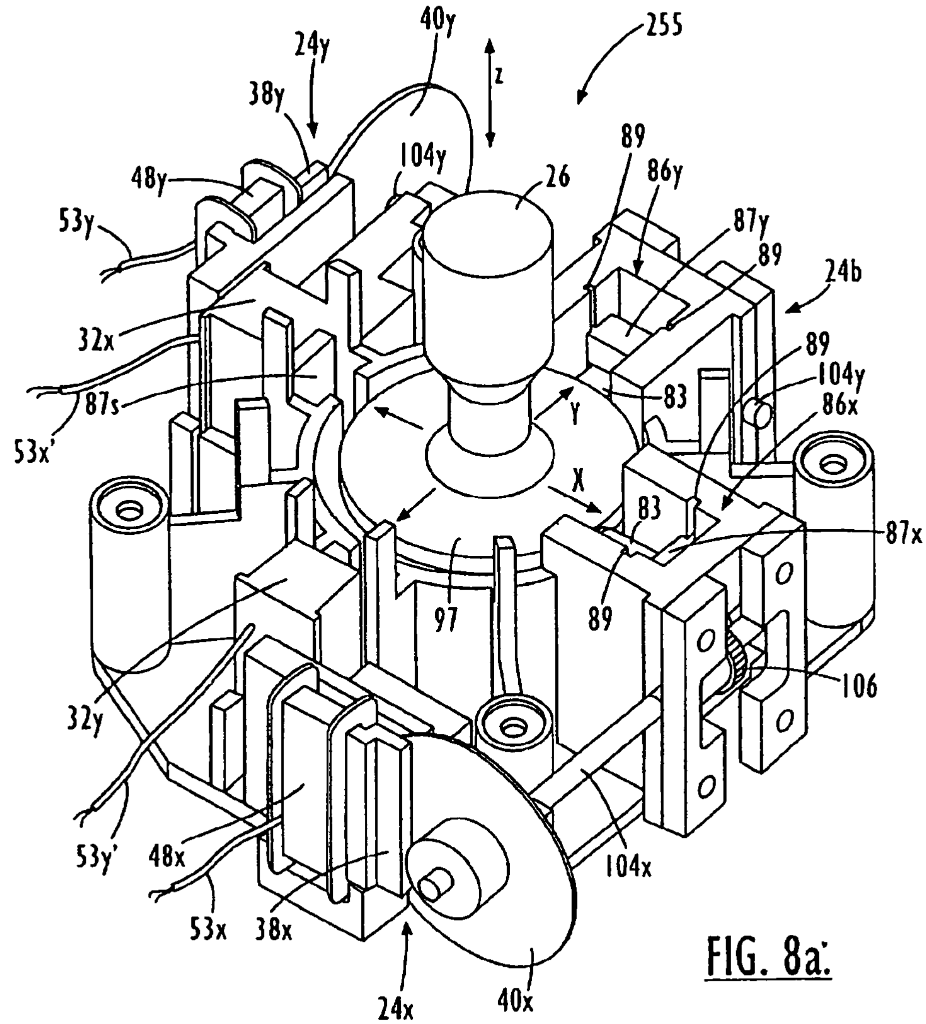

255
40y
24y
38y
48y
53y
104y
z
26
89
86y
87y
89
24b
32x
87s
53x'
89
104y
86x
83
Y
X
83
87x
97
89
106
32y
53y'
48x
53x
38x
104x
24x
40x

FIG. 8a.

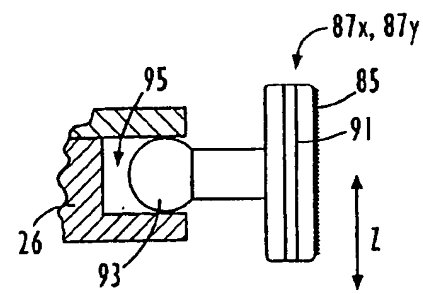

87x, 87y
95
85
91
26
93
Z

FIG. 8b.

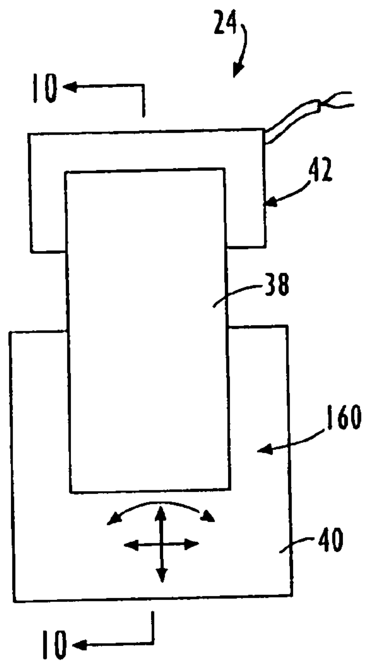


FIG. 9.

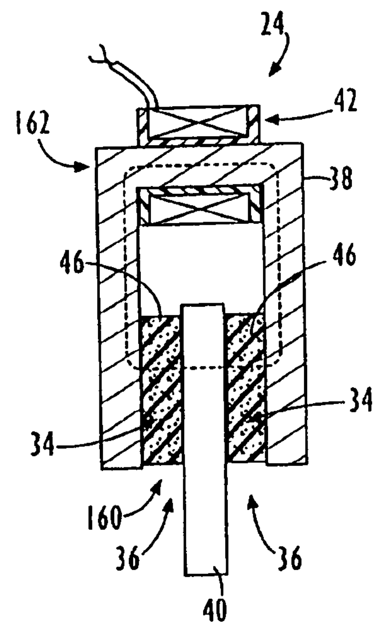


FIG. 10.

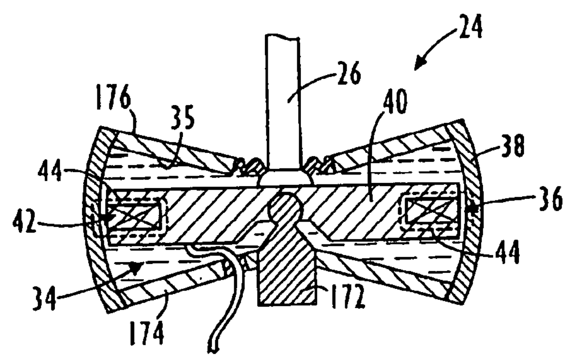


FIG. 11.

MAGNETICALLY-CONTROLLABLE, SEMI-ACTIVE HAPTIC INTERFACE SYSTEM AND APPARATUS

CROSS REFERENCE COPENDING APPLICATION

[0001] The present application is a continuation-in-part application of copending U.S. patent application Ser. No. 09/189,487, filed Nov. 10, 1998.

FIELD OF THE INVENTION

[0002] The present invention relates generally to a haptic interface system for providing force feedback sensations, and more particularly, to a haptic interface system employing a magnetically-controllable medium to provide resistance forces.

BACKGROUND

[0003] Haptic interface systems, also known as force feedback systems, provide an operator holding an interface device, such as a joystick or steering device, with "feel" or tactile sensations in response to whatever is being controlled by the interface device. The haptic interface system is often used for controlling the steering and operation of vehicles and machinery. Frequently such devices are used in combination with a computer game. In such a game, the action on a video display and the movement of a joystick or steering device are coordinated with physical force imparted to the operator's hand through the joystick or steering device, to provide a simulated "feel" for events happening on the display. For example, in an auto racing game, when an operator steers a car around a sharp turn at high speed, the haptic interface system imparts force on the steering wheel to make it more difficult to turn the wheel into the curve. This force feedback simulates the centrifugal force of the car making the turn and the friction forces applied to the tires as they are turned. Thus, haptic interface systems provide remote simulation of the actual physical feeling associated with an action or event through force feedback.

[0004] Typical haptic interface systems include one or more motors connected to the interface device in order to impart the force feedback sensation. Typical motors include direct current (DC) stepper motors and servo-motors. If the interface device is a joystick, motors are used to impart force in an x-direction, in a y-direction, or in combination to provide force in any direction that the joystick may be moved. Similarly, if the interface device is a steering wheel, motors are used to impart rotational force in a clockwise or counterclockwise direction. Thus, motors are used to impart forces in any direction that the interface device may be moved.

[0005] In a system using a single motor, the motor may be connected to the interface device through a gear train, or other similar energy transfer device, in order to provide force in more than one direction. In order to enable one motor to be used in a system, a reversible motor is typically utilized to provide force in two different directions. Additionally, mechanisms are required to engage and disengage the various gears or energy transfer devices to provide force in the proper direction at the proper time. In contrast, other typical systems use more than one motor to provide force in the required directions. Thus, current systems utilize a number of differing approaches to handle the delivery of force feedback sensations.

[0006] Current haptic interface systems may be disadvantageous, however, for a number of reasons. One primary area of concern is the cost of such systems. One item greatly contributing to the cost of a typical system is the use of DC stepper and servo-motors, and reversible motors. These types of motors are very sophisticated, requiring the ability to change speeds or rotations per minute (rpm), maintain different speeds, and reverse rotational direction. These features require greater mechanical and electrical complexity, which equates to a comparatively very high cost. Further, these motors need to be small in size in order to keep the haptic interface system from becoming unwieldy. This additionally complicates their design and increases cost. Also, because of their relatively small size, the sophisticated motors typically required in a haptic interface system are only able to generate a limited amount of torque. As such, the operator of an interface device may easily be able to overcome the torque or force feedback supplied by the motor. Thus, providing a small, sophisticated motor for a haptic interface system is relatively very costly, and may result in insufficient force feedback.

[0007] Also disadvantageously, typical DC motors used in haptic interface systems are not designed to perform in the manner required by the system. In order to provide force feedback, typical systems use direct drive motors configured to mechanically engage the output shaft of the motor with the interface device. For example, the output shaft of a DC motor may be geared to a steering wheel shaft or linked to a slide or other mechanism controlling the movement of a joystick. When the motor engages the gear or slide, the motor drives the interface device to provide force feedback. The operator holding the interface device, however, typically opposes the force feedback. The opposing force supplied by the operator then works against the direction of the motor output, which tends to stall the motor. Not only does this opposing force tend to wear out and/or strip components within the motor, but the stall condition leads to the generation of higher electric currents within the motor, straining the electrical components in the motor. Due to the repetitious nature of a haptic interface system, the reliability and longevity of motors in such haptic interface systems are severely reduced. Thus, motors used in typical haptic interface systems are typically not very well suited for the demanding environment in which they are operated.

[0008] Yet another disadvantage of current commercial haptic interface systems is that high impact forces from a motor connected to an interface device may be dangerous for the operator of the interface device. When the haptic interface system requires a quick, high impact force, a motor connected to an interface device may respond with a large force that may injure the operator if the operator is not ready for the abrupt force. This may be accounted for by ramping up the speed of the motor to achieve the force, but then the sensation becomes less realistic. Further, varying the engagement speeds of the motor complicates the software program that is used to run the haptic interface system, thereby further increasing cost. Thus, producing a realistic-feeling high impact force with current haptic interface systems may be dangerous to the operator or may require costly and complex system programming.

[0009] Some prior art devices have attempted to overcome some of the drawbacks of current haptic interface systems, with limited results. An electrorheological (ER) actuator, utilized in a force display system, is proposed by J. Furusho and M. Sakaguchi entitled "New Actuators Using ER Fluid And Their Applications To Force Display Devices In Virtual

Reality Systems," in abstracts of the International Conference On ER Fluids, MR Suspensions and their Applications, Jul. 22-25, 1997 Yonezawa, Japan, pg. 51-52. An ER actuator comprises a device that contains an ER fluid, which is a substance that changes its shear strength with application of an electric field. The ER fluid can then be used as a clutch or a brake to increase resistance between two members.

[0010] The use of such an ER actuator is severely disadvantageous, however, for use in typical haptic interface systems. One major issue is that an ER actuator presents a major safety problem because of the high electric voltage required to produce the electric field necessary to generate a desired change in shear strength in the ER fluid. For a haptic interface system, a typical ER fluid actuator may require voltages in the range of about 1000 to 5000 volts. Conversely, the motors used in the typical systems described above require in the range of about 500 milliamps (mA) to 1.0 A of current. Thus, the voltage required to operate an ER actuator is very high, making an ER actuator undesirable, and possibly unsafe, for a consumer device subject to a great amount of wear and tear.

[0011] Additionally, an ER actuator detrimentally requires expensive seals to hold the ER fluid within cavities within the actuator. Seals frequently wear, causing reliability problems for ER actuators and concerns about ER fluid leaks. Further, the use of seals typically requires machined parts having tight tolerances, additionally increasing the cost of the ER actuator. Also, ER actuators require expensive bearings to insure the relative positioning of the tight-tolerance parts.

[0012] Similarly, precise machining is required for the internal rotating components of an ER actuator, further increasing the cost of the actuator. Because an ER device requires a relatively large amount of surface area between the ER fluid and the two members that the ER fluid contacts, tight tolerance machining is needed between the multiple, adjacent surfaces of the members. Thus, a relatively large amount of surface area may be required to generate sufficient torque to provide the levels of force feedback required by typical haptic interface systems.

[0013] Finally, typical ER actuators that provide appropriate force may be too large to be integrated into a commercial haptic interface system. The device utilized to provide force feedback in a typical haptic interface system must be small and lightweight in order to be practically integrated into the system. An ER actuator meeting these requirements is very costly to produce, besides having the above-stated deficiencies. Thus, utilization of an ER actuator in a typical haptic interface system is not desirable.

[0014] Therefore, it is desirable to provide a haptic interface system that is more simple, cost-effective, reliable and better performing than the above-stated prior art.

SUMMARY OF THE INVENTION

[0015] According to a preferred embodiment of the present invention, a haptic interface system of the present invention comprises a magnetically-controllable device that advantageously provides a variable resistance force that opposes movement of a haptic interface device to provide force feedback sensations. The haptic interface device is in operative contact with the operator of a vehicle, machine or computer system. The magnetically-controllable device beneficially comprises a magnetically-controllable medium between a first and second member, where the second member is in communication with the haptic interface device. For purposes of this description, the magnetically controllable medium shall include any magnetically controllable material such as a magnetorheological fluid or powder. The magnetically-controllable medium provides the variable resistance force, in proportion to the strength of an applied magnetic field, that opposes relative movement between the first and second members. The haptic interface system of the present invention may be used to control vehicle steering, throttling, clutching and braking; computer simulations; machinery motion and functionality. Examples of vehicles and machinery that might include the haptic interface system of the present invention comprise industrial vehicles and watercraft, overhead cranes, trucks, automobiles, and robots. The haptic interface device may comprise, but shall not be limited to a steering wheel, crank, foot pedal, knob, mouse, joystick and lever.

[0016] Furthermore, the controller may send signals to the vehicle, machine or computer simulation **30** in response to information obtained by sensor **32** and other inputs **30** for purposes of controlling the operation of the vehicle, machine or computer simulation. See **FIGS. 1A and 1B**. Once the operator inputs and other inputs are processed by micrprocessor **54**, a force feedback signal is sent to the magnetically controllable device **24** which in turn controls the haptic interface **26** such as a joystick, steering wheel, mouse or the like to reflect the control of the vehicle, machine or computer simulation.

[0017] The system additionally comprises a controller, such as a computer system, adapted to run an interactive program and a sensor that detects the position of the haptic interface device and provides a corresponding variable input signal to the controller.

[0018] The controller processes the interactive program, and the variable input signal from the sensor, and provides a variable output signal corresponding to a semi-active, variable resistance force that provides the operator with tactile sensations as computed by the the interactive program. The variable output signal energizes a magnetic field generating device, disposed adjacent to the first and second members, to produce a magnetic field having a strength proportional to the variable resistance force. The magnetic field is applied across the magnetically-controllable medium, which is disposed in a working space between the first and second members. The applied magnetic field changes the resistance force of the magnetically-controllable medium associated with relative movement, such as linear, rotational or curvilinear motion, between the first and second members in communication with the haptic interface device. As such, the variable output signal from the controller controls the strength of the applied magnetic field, and hence the variable resistance force of the magnetically-controllable medium. The resistance force provided by energizing the magnetically-controllable medium controls the ease of movement of the haptic interface device among a plurality of positions. Thus, the present haptic interface system provides an operator of a vehicle, machine, or computer simulation, force feedback sensations through the magnetically-controllable device that opposes the movement of the haptic interface device.

[0019] In a preferred embodiment, the magnetically-controllable medium within the magnetically-controllable device is contained by an absorbent element disposed between the first and second member. The absorbent element may be compressed from a resting state, preferably in the amount of about 30%-70% of the resting state. The absorbent element may be formed as a matrix structure having open spaces for retaining the magnetically-controllable medium. Suitable materials for the absorbent element comprise open-celled foam, such as from a polyurethane material, among others.

[0020] The magnetically-controllable medium is a medium having a shear strength that varies in response to the strength of an applied magnetic field. One preferred type of magnetically-controllable medium is a magnetorheological fluid. As mentioned above, the magnetic-field generating device provides the applied magnetic field. The magnetic-field generating device is preferably a coil and comprises a wire having a number of turns and a certain gauge. The number of turns and gauge of the wire are dependent upon the desired range of the variable strength magnetic field and upon the electric current and voltage of the variable output signal.

[0021] As previously indicated hereinabove, the controller may comprise a computer system further comprising a host computer, a control unit and an amplifier. The control unit and amplifier, as is explained below, may alternatively be separate components or part of a haptic interface unit. The host computer comprises a processor that runs the interactive program. The control unit comprises a microprocessor and firmware that are used to modify the variable input signal received from the sensor and the variable output signal received from the host computer. The control unit then provides a modified variable input signal to the host computer and a modified variable output signal to the magnetically-controllable device. The modification function performed by the control unit enables communication between the host computer and the magnetically-controllable device and the sensor. The amplifier further modifies the output signal to provide an amplified variable output signal in situations where the output signal from host computer is not sufficient to control the magnetically-controllable device. Further, the control unit and amplifier may act as local processors, reducing the burden on the host computer by providing output signals for certain input signals, such as to provide reflex-like resistance forces, that do not need to be processed by the host computer.

[0022] In one embodiment, the present invention discloses a haptic interface unit comprising the magnetically-controllable device, as described above, is adapted to provide a variable resistance force in proportion to a received variable output signal generated by a computer system processing an interactive program. The magnetically-controllable device further comprises a magnetic-field generating device, first and second members, and a magnetically-controllable medium. The magnetic-field generating device is energizable by the variable output signal to provide a variable strength magnetic field. The first and second members are adjacent to the magnetic field generating device. The magnetically-controllable medium is disposed between the first and second members, where the magnetically-controllable medium provides the variable resistance force in response to the variable strength magnetic field. Additionally, the haptic interface unit may further comprise a haptic interface device, adapted to be in operable contact with the operator, for controlling and responding to the interactive program. The haptic interface device is in communication with the magnetically-controllable device and has a plurality of positions, wherein an ease of movement of the haptic interface device among the plurality of positions is controlled by the variable resistance force. Finally, the haptic interface unit may further comprise a control unit that provides a signal to the magnetically-controllable device to control the variable resistance force.

BRIEF DESCRIPTION OF THE DRAWINGS

[0023] **FIG. 1A** is a schematic block representation of the haptic interface system according to the present invention.

[0024] **FIG. 1B** is a schematic block representation of a haptic interface system according to the present invention for use in a computer simulation application.

[0025] **FIG. 1C** is a schematic block representation of a haptic interface system according to the present invention for use in a vehicle or machine steering application.

[0026] **FIG. 1D** is a schematic block representation of a haptic interface system according to the present invention for use in a vehicle or machine joystick application.

[0027] FIGS. 2A-2B are a perspective view and a cross-sectional view, respectively, of a typical magnetically-controllable device.

[0028] **FIG. 3** is a partial cross-sectional view of one embodiment of a haptic interface unit.

[0029] **FIG. 4*a*** is a cross-sectional view along line **4-4** in **FIG. 3** of one embodiment of a magnetically-controllable device.

[0030] **FIG. 4*b*** is a cross-sectional view of an alternate embodiment of a magnetically-controllable device.

[0031] **FIG. 5** is a partial cross-sectional rear view of another embodiment of a haptic interface unit, with some components removed for clarity, utilizing the magnetically-controllable device of **FIGS. 3 and 4**.

[0032] **FIG. 6** is a partial cross-sectional side view of the haptic interface unit of **FIG. 5**, with some components removed for clarity.

[0033] **FIG. 7*a*** is a partial cross-sectional top view taken along line **7*a*-7*a*** of **FIG. 5**, with some components removed for clarity.

[0034] **FIG. 7*b*** is a top view of the sensor which interconnects to the plates of **FIG. 7*a*;**

[0035] **FIG. 8*a*** is a perspective view of yet another embodiment of a haptic interface unit.

[0036] **FIG. 8*b*** is a side view of the rack of **FIG. 8*a*.**

[0037] **FIG. 9** is a side view of yet another embodiment of a magnetically-controllable device.

[0038] **FIG. 10** is a cross-sectional view along line **10-10** of the device in **FIG. 9**.

[0039] **FIG. 11** is a cross-sectional view of another embodiment of a magnetically-controllable device.

DETAILED DESCRIPTION OF THE INVENTION

[0040] According to the present invention a semi-active haptic interface system 20 is illustrated schematically in FIG. 1A. The semi-active haptic interface system 20 provides resistance forces to an operator 22 and comprises a magnetically-controllable device 24 that imparts force feedback resistance sensations to the operator through a haptic interface device 26 by opposing the movement of the haptic interface device. Operator 22 moves haptic interface device 26 to control and respond to a control program or algorithm executed by the controller 28. Signals relating to the application where the system is located such as a vehicle, machine or computer simulation are sent by the output device 30 to controller 28 where they are processed in order to determine the required effect on magnetically-controllable device 24. The output device may comprise a monitor, with corresponding images displayed on the monitor 30. A sensor 32 detects the movements of haptic interface device 26 and reports the movements to controller 28. The controller 28 for purposes of the description of the preferred embodiment of the invention is a computer system 28 that interactively responds by generating new images on monitor 30 and by controlling magnetically-controllable device 24 to provide a variable resistance force corresponding to the movement of haptic interface device 26 and corresponding to the images on the monitor 30. Thus, haptic interface system 20, and particularly magnetically-controllable device 26, advantageously provide a simple, cost-effective, high-performance solution for supplying a semi-active resistance force enabling operator 22 to feel realistic force feedback sensations.

[0041] When the system is installed in a vehicle or machine the system may not include a monitor. The monitor would be included in a computer simulation application of the invention as shown in FIG. 1B.

[0042] The semi-active feature of haptic interface system 20 of the present invention is particularly beneficial in providing a very cost-efficient, compact and robust system. As used herein, the term "semi-active" refers to the ability to provide a dissipative opposing resistance force in response to an applied motion. In contrast to prior art haptic interface systems that provide "active" force feedback utilizing expensive motors, haptic interface system 20 of the present invention advantageously utilizes magnetically-controllable device 24 including a magnetically controllable medium 34 (FIG. 2A) to provide semi-active, variable resistance forces. The term "active" refers to the ability to independently impart a force to the haptic interface device without requiring the operator to move the device. Through continual feedback between haptic interface device 26 and controller 28, the controller directs magnetically-controllable device 24 to provide variable resistance forces that oppose the movement of the haptic interface device 26. Further, based on running the interactive program, controller 28 directs the resistance provided by magnetically-controllable device 24 to vary in conjunction with images on display 30 and/or with the movement of the haptic interface device 26.

[0043] For example, if the operator is controlling a computer simulation of FIG. 1B such as a race car driving interactive program, and operator 22 attempts to move haptic interface device 26 in a direction that steers the car into a non-destructible wall, then the computer system will provide a control signal. The signal controls magnetically-controllable device 24 to provide resistance forces equal to or greater than the force applied to the haptic interface device by the operator. This opposes any movement of the haptic interface device and simulating the feel of driving into an immovable wall.

[0044] Similarly, given the same interactive race car driving program and operator 22 driving the car around a curve, controller 28 provides a variable amount of resistance force less than the force applied by operator 22 to haptic interface device 26 to simulate the actual centrifugal and friction forces. The amount of the variable resistance force depends upon the speed and traction of the car and the sharpness of the curve, for example. As a result, magnetically-controllable device 24 creates resistance force feedback sensations felt by operator 22 through haptic interface device 26, giving the interactive program a realistic feel. Thus, as operator 22 maneuvers haptic interface device 26, the system of the present invention supplies resistance to oppose the motion of the haptic interface device to simulate real-life forces. As indicated hereinabove, the haptic interface system of the present invention may be used to control vehicle steering, throttling and braking; computer simulations; machinery motion and functionality. However as the description of the haptic interface system of the present invention proceeds, for purposes of describing the operation of the invention the system will be used to control computer simulations. Schematic representations of the system 20 integrated in the vehicle/machine steering wheel or joystick are shown in FIGS. 1C and 1D.

[0045] Magnetically-controllable device 24 beneficially contributes to the cost-efficient, compact and robust design of haptic interface system 20. Referring to FIGS. 2A and 2B, a typical magnetically-controllable device 24 generally comprises a magnetically-controllable medium 34 contained in a working space 36 between first member 38 and second member 40. Members 38, 40 are disposed for relative movement along the mating surfaces, such as linear or rotational motion as indicated by the arrows. Magnetically-controllable medium 34 is under the influence of an annular-shaped magnetic-field generating device 42 (FIG. 2B) energizable to produce a variable strength magnetic field across the medium. Magnetically-controllable medium 34 is a medium that has a shear strength that changes in proportion to the strength of an applied magnetic field. In other words, the "apparent viscosity" of the medium changes proportionally with the strength of an applied magnetic field, providing controllable shear force to resist relative movement between members 38, 40.

[0046] A suitable magnetically-controllable medium 34 may comprise magnetorheological fluids such as described in commonly assigned U.S. Pat. Nos. 5,683,615 and 5,705,085 hereby incorporated by reference. Other fluids, such as carbonyl iron dispersed in hydrocarbon oil, or and any medium exhibiting a change in properties in response to an applied magnetic field. Other magnetorheological fluids which may be used in the present invention are disclosed in, for example, U.S. Pat. No. 5,382,373 to Carlson et al. and U.S. Pat. No. 5,578,238 to Weiss, et al., hereby incorporated by reference.

[0047] First 38 and second 40 members are adjacent to magnetic-field generating device 42, and disposed at least partially on opposing sides of magnetically-controllable medium 34. Members 38, 40 each preferably include a highly magnetically permeable material, such as a magnetically soft steel such as AISI 1010, AISI 1018 or AISI 12L14 in order to act as pole pieces to produce a magnetic field across medium 34, as indicated by flux lines 44. Additionally, second member 40 is in communication with haptic interface device 26, such that operator 22 moving the haptic interface device during energization of magnetic-field generating device 42 feels the changed resistance force generated between first 38 and second 40 members by magnetically-controllable medium 34. Significant shear force resisting the relative movement of first member 38 and second member 40 can advantageously be obtained with a small amount of magnetically-controllable medium 34 between movable members 38, 40. Thus, a variety of relative movements, such as linear, rotational, curvilinear, and pivoting, that include shear movement between two members can be controlled by a magnetically-controllable device according to the present invention.

[0048] Additionally, magnetically-controllable device 24 preferably contains substantially the entire amount of magnetically-controllable medium 34 at working space 36. Any suitable means for containing medium 34 at working space 36 can be used. According to a preferred embodiment of the invention, means for containing magnetically-controllable medium 34 within working space 36 comprises an absorbent element 46. Absorbent element 46 is a material that can take up and hold magnetically-controllable medium 34, for example by wicking or capillary action. Absorbent element 46, disposed between first member 38 and second member 40, preferably has a matrix structure with open spaces for retaining magnetically-controllable medium 34. While magnetically-controllable medium 34 is held within the spaces in absorbent element 46, the material itself may or may not be absorbent. A complete description of such devices may be found in U.S. patent application Ser. No. 08/959,775 to Carlson filed Oct. 29, 1997 entitled "Controllable Medium Device And Apparatus Utilizing Same."

[0049] A particularly preferred absorbent element 46 is a sponge-like material, for example, an open-celled foam or partly open-celled foam. Suitable materials for making such a foam comprise polyurethane, rubber, silicone rubber, polyamide, neoprene, loner, melamine, polyimide high temperature foam, and metal foam. Additionally, other exemplary absorbent materials include felts, including felts mad of material such as Nomex® aramid fiber, polybenzimadazole fiber, Teflon® fiber and Gore-Tex® fiber, fiberglass wicking, and woven brake or clutch lining material. Other materials and structures are also suitable, such as a metal mesh, a brush, or a flocked surface material.

[0050] Absorbent element 46 also beneficially allows for reduced tolerances between the components of magnetically-controllable device 24, thereby reducing the cost to manufacture and assemble device 24. In order to negate the affects of wear at the surface of absorbent element 46, and to provide a robust design, it is desirable to have the material compressed between member 38, 40. Absorbent element 46 may be utilized without any compression, but the material is preferably compressed between about 30% and 70% from a resting state to its installed state. Thus, by containing substantially the entire amount of controllable medium 34 at working space 36 and allowing for wear and tear of absorbent element 46, the present invention avoids the need to provide a large quantity of medium, and the associated seals, bearings and containing devices of the prior art. Accordingly, the present invention reduces the tight tolerances formerly needed on all components.

[0051] Absorbent element 46 is preferably fixed to one of the relatively moving members 38, 40 to ensure that it remains disposed in the working space 36. According to a preferred embodiment, absorbent element 46 is adhesively bonded using a pressure sensitive adhesive to one of the members. One preferred absorbent element 46 is polyurethane foam having a pressure sensitive adhesive on one side. The foam may be readily attached to one member by the adhesive. Alternatively, absorbent element 46 may be shaped so that it is held in place by the structure of the member, for example, a tubular shaped foam material may be fitted around a member as a sleeve. Finally, absorbent element 46 does not need to fill working space 36.

[0052] Referring to FIGS. 2A-2B, magnetic-field generating device 42 preferably comprises at least one coil 48 formed of an electrically-conducting wire wound about a retainer 50, such as a plastic bobbin or spool. The windings of wire forming coil 48 are wound such that energizing the coil with electricity produces an induced magnetic field, represented by flux lines 44, that intersects magnetically-controlled medium 34. The induced magnetic field is proportional to the electric current supplied to energize the coil 48, such as from the output signal of computer system 28 and number of turns of wire. The wire forming coil 48, as will be realized by one skilled in the art, may be selected from a broad range of electrically-conducting materials, depending on the range of the desired magnetic field strength, the range of desired electrical current, space constraints, and desired operating voltage. For example, wire may comprise materials such as copper, aluminum, gold, silver and the like. Similarly, the gauge of the wire and the number of windings within coil 48 are dependent upon the application, and can be determined by methods known by one skilled in the art.

[0053] Magnetic field generating device 42 may be adjacent first member 38 or second member 40, but is preferably disposed within a recess 52, such as annular recess shown, formed within one of members (shown within first member 38 in **FIG. 2B**). The lead wires 53 (**FIG. 2A**) connecting to coil 48 are connected to controller 28 , which provides a signal 66' (shown in detail in **FIG. 1A**) to energize the coil, as is discussed in further detail below. Because the wires 53 connecting coil 48 may be mounted to a moving member, there may be a need to restrict the movement of that member in order to avoid breaking the wire by excessive stretching, bending or rotation of the wires. Alternatively, means may be provided to enable a connection to controller 28 even with excessive linear, rotational, pivotal or curvilinear movement. For example, a slip-ring connector, a wire take-up reel, and a coiled wire may be utilized to allow for great amounts of movement while maintaining a reliable connection. These alternatives are generally more costly, however, and thus are not as desirable for a cost efficient haptic interface system.

[0054] Referring to **FIG. 1A**, magnetically-controllable device 24 is preferably integrated with haptic interface device 26 and sensor 32 to comprise a haptic interface unit (as represented by the dashed line 55). The haptic interface

unit 55 may additionally comprise a control unit 54 and/or a signal amplification device 56, as will be discussed in more detail below. The haptic interface unit 55 may further comprise a protective housing or shell within which each of the above-mentioned components are mounted.

[0055] Haptic interface device 26 may be any device in operable contact with operator 22. Operator 22 maneuvers haptic interface device 26 to control and respond to the interactive program processed by the computer system of controller 28. A suitable haptic interface device 26 may comprise a steering wheel, a joystick, a steering yoke, a crank, a foot pedal, a knob, a mouse, a lever, a seat, a motor bike frame, a jet ski frame, a downhill ski frame, amusement part ride, and any other device in operable contact with operator 22.

[0056] Sensor 32 is in communication with haptic interface device 26 for identifying a detected position within any of the plurality of positions within which the haptic interface device may be moved. Sensor 32 provides a variable input signal to controller 28 based on the detected position. Because haptic interface device 26 may be continually moving, sensor 32 must quickly provide controller 28 with an updated detected position of the haptic interface device 26 in order to allow the controller 28 to update its output signal to provide the operator with tactile sensations as computed by the interactive program. Ideally, sensor 32 provides control unit 54 with a continuous signal that varies in proportion to the movement of the detected position of the haptic interface device 26.

[0057] Suitable sensors may comprise a potentiometer, such as Clarostat 10K ohm potentiometer, an optical encoder, such as a Clarostat Series 6000 optical rotary encoder, or any type of rheostat or variable resistor. For example, sensor 32 may be mounted on a shaft connected to a steering wheel to detect the rotation of the steering wheel. Also, more than one sensor 32 may be required to detect complex movements of haptic interface device 26. For example, if haptic interface device 26 is a joystick, one sensor 32 may be connected to a component of the joystick to determine a movement in the x-direction, while another sensor 32 may be connected to another component of the joystick to determine a movement in the y-direction. In this example, the x-direction sensor and the y-direction sensor may each send a variable input signal to controller control unit 54.

[0058] Control unit 54 receives the variable input signal from sensor 32 and provides a variable output signal to magnetically-controllable device 24. As discussed above, there is a continual feedback loop between the control unit 54 of controller 28 and haptic interface device 26, and hence between host computer 58, magnetically-controllable device 24 and sensor 32. The interactive program being processed by host computer 58 uses the variable input signal from sensor 32 as an input to the interactive program. Based upon this input, the host computer 58 further processes the control program to determine the variable output signal to send to magnetically-controllable device 24. Returning to the previously presented example of operator 22 controlling a computer system, in such a computer system, the control or interactive program within host computer 58 processes an input signal from sensor 32. From this, the host computer 58 determines a semi-active resistance force required from magnetically-controllable device 24 in order to coordinate what operator 22 is viewing on display 30 with what the operator is feeling through haptic interface device 26 in order to simulate tactile sensations. Host computer 58 sends a signal to display 30 to update the displayed image, and concurrently sends an output signal to magnetically-controllable device 24. The output signal sent to magnetically-controllable device 24, for example, may be an electric current having a value in proportion to a resistance force desired to be felt by operator 22. Thus, in attempting to move haptic interface device 26, operator 22 feels the change in resistance force applied by magnetically-controllable device 24 through the haptic interface device, thereby providing force feedback sensations.

[0059] While, in general, controller 28 receives a variable input signal from sensor 32 and generates a variable output signal to magnetically-controllable device 24, a number of different components may be involved in the signal transactions. Controller 28 may comprise host computer 58, and may further include control unit 54 and amplification device 56 to communicate with haptic interface device 26. Host computer 58 typically includes an input/output 60 for sending/receiving electrical signals, a processor 62 and a memory 64 for respectively processing and storing electrical signals representative of an interactive program, for example. A suitable host computer 58 is, for example, a personal computer such as a IBM, Compaq, Gateway or other suitable computer capable of processing the appropriate information. Input/output 60 may comprise a plurality of serial and/or parallel communication ports, such as RS-232 type ports, and high-speed bi-directional communication channels like the Universal Serial Bus (USB). Processor 62 may comprise an Intel Pentium ® or other suitable microprocessor. Memory 64 may comprise Random Access Memory (RAM) and Read-Only Memory (ROM), as well as other well-known types of memory. As one skilled in the art will appreciate, depending upon the particular application, there is a broad range of personal computers, input/outputs, microprocessors and memories that may be utilized with the present invention.

[0060] For example, host computer 58 may send output signal 66 comprising an electric current proportional to a desired resistance force to be applied to haptic interface device 26. Output signal 66 may be received by control unit 54 for additional processing. Control unit 54 may be a microcomputer having an input/output 68, a processor 70, such as a digital signal processor (DSP), for processing electrical signals, a memory 72 for storing electrical signals, and/or firmware 74 that stores and processes electrical signals, where the electrical signals are representative of a local interactive program or inputs from other devices with system 20. Input/output 68, microprocessor 70, and memory 72 may be substantially similar to those described above for host computer 58, however, the capabilities of control unit 54 may be more limited to reduce cost. Control unit 54 processes output signal 66 from host computer 58 and provides a modified output signal 66'.

[0061] Additionally, control unit 54 may locally process signals or portions of signals directly received from components within system 20. For example, control unit 54 may receive variable input signal 76 from sensor 32 and search the signal for portions that may be processed locally before passing the input signal on to host computer 58 as modified

variable input signal 76'. Also, control unit 54 may provide modified input signal 76' to place input signal 76 in a format that may be understood or processable by host computer 58. Further, control unit 54 may receive input signal 78 from haptic interface device 26, such as a signal from a button or trigger 79 on the haptic interface device. Input signal 78 may be a signal that requires a reflex-like response, such as the firing of a gun. Rather than burdening host computer 58 with processing these types of signals, which may be very frequent, control unit 54 provides the processing capability. Input signal 78 may be completely processed by control unit 54, thereby advantageously reducing the processing burden on host computer 58. Thus, the use of control unit 54 increases the efficiency of system 20 by performing force feedback computations in parallel with the force feedback computations being performed by host computer 58 in running the interactive program.

[0062] Similarly, control unit 54 may receive concise high-level commands, comprising all or a portion of output signal 66, to be processed locally within the control unit 54. These high-level commands may represent simple, semi-active, variable resistance force sensations that may be easily processed locally by control unit 54. Thus, in effect, control unit 54 provides a parallel processing capability to host computer 58 to maximize the overall efficiency of system 20.

[0063] Modified variable output signal 66' provided by control unit 54 may require further processing before being received by magnetically-controllable device 24. Modified output signal 66' may be received by amplification device 56, for example, to boost the level of modified output signal 66' to provide amplified output signal 66". Modified output signal 66' may be a variable signal of low electrical current that is not sufficient to properly energize coil 48 to produce a magnetic field to the desired strength to provide the desired resistance forces. To solve this problem, amplification device 56 proportionally increases the strength or amperage of modified output signal 66' to a level sufficient to properly energize coil 48. Thus, amplification device 56 advantageously allows lower strength signals to be processed within system 20, thereby saving cost by requiring less heavy duty components and less power, before boosting the signal to a level required to properly energize magnetically-controllable device 24.

[0064] As mentioned above, control unit 54 and amplification device 56 may be a part of computer system 28 or the haptic interface unit or they may be separate components within system 20. Those skilled in the art will realize that the various components described above may be combined in numerous manners without affecting the operability of the system. Similarly, some of the components, such as control unit 54 amplification device 56, may not be required if their function can be adequately performed by other system components, such as host computer 58. Thus, variation of the above-described configuration of system 20 is contemplated by the present invention.

[0065] Haptic interface system 20 comprises two closely coupled, interactive functions: a sensory input function and a force output function. The sensory input function tracks the operator's manual manipulation of the haptic interface device, feeding sensory data to the controller representative of those manipulations. The force output function provides physical tactile feedback to the operator in response to commands from the host computer. These two functions are intertwined in that the sensory input function generally varies in response to the force output function, and vice versa. In other words, the operator's manipulations of the haptic interface device are affected by the applied resistance forces, or force feedback, and the applied resistance forces are dependent upon the manipulations of the operator. Thus, haptic interface system 20 involves a very complex and continual interaction.

[0066] Returning again to the example of the computer system operator 22, in operation, host computer 58 runs an interactive program, such as a game, using processor 62 to generate a video signal 80 received by display 30. Video signal 80 is an electrical signal used to generate an image, corresponding to an event occurring within the game, on display 30. Operator 22 responds to the event by moving haptic interface device 26, such as a steering wheel or a joystick, in conjunction with the viewed event. Sensor 32 sends variable input signal 76 comprising tracking information representing the position of the wheel or joystick to control unit 54. Control unit 54 may respond to the information by processing the information locally, and by forwarding the information, or a modified form of the information, as a modified variable input signal 76' to host computer 58. Even when processing information locally, control unit 54 may provide modified variable input signal 76' to host computer 58 and/or display 30 to update the generated image of the event to correspond with the latest input.

[0067] Host computer 58 receives modified variable input signal 76' from control unit 54 and inputs that information into processor 50 that is running the interactive game. Host computer 58, based on the processing of modified input variable signal 76', updates the image of the event generated on display 30 and provides a variable output signal 66 in proportion to a resistance force to be felt by operator 20 in moving the wheel or joystick. Variable output signal 66 may be modified by control unit 54 and amplified by amplification device 56 before reaching magnetically-controllable device 24 as amplified variable output signal 66". The strength of amplified variable output signal 66" varies in proportion to a desired magnetic field strength, and hence resistance force, as computed by host computer 58 to coordinate with the interactive program.

[0068] Again referring to FIGS. 1B, 2A and 2B, variable output signal 66" thereby energizes coil 48 within magnetically-controllable device 24 to produce a magnetic field. The magnetic field is applied across working space 36, affecting the shear strength of magnetically-controllable medium 34 contained within absorbent element 46. The affect on the shear strength of medium 34 creates a semi-active, resistance force between first 38 and second 40 members, which is connected to haptic interface device 26. As a result, operator 22 feels the changed resistance force through haptic interface device 26 during attempted movements of the haptic interface device. Thus, haptic interface system 20 provides opposing force feedback sensations, or resistance forces, to operator 22 maneuvering haptic interface device 26 to simulate a realistic feel. For example, the following feels may be simulated: jolting blasts, rigid surfaces, viscous liquids, increased gravity, compliant springs, jarring vibrations, grating textures, heavy masses, gusting winds, and any other physical phenomenon that can be represented mathematically and computed by controller 28.

[0069] The following comprises a number of different embodiments employing the teachings of the present invention. Where elements are substantially the same as those discussed above, they are given the same reference numeral. Based on the variety of mechanisms utilized by various manufacturers to reduce the movement of a haptic interface device into manageable and measurable components, such as movements in an x-direction and a y-direction, numerous configurations of haptic interface systems utilizing the teachings of this invention may be employed. Thus, these examples are not intended to be limiting, but are exemplary of the teachings of the present invention to numerous embodiments of haptic interface systems.

[0070] In general, the movement of a haptic interface device 26 is either linear or rotary, which includes partial rotation or curvilinear motion. Similarly, a magnetically-controllable device 24, as mentioned above, is capable of providing opposing variable resistance force to either linear or rotary movements, including partial rotation or curvilinear motion. To control the movements of the haptic interface device 26, the magnetically-controllable device 24 must somehow be linked to the haptic interface device 26. As such, the linking mechanisms typically translate the following types of movement from the haptic interface device 26 to the magnetically-controllable device 24: linear to linear; linear to rotational; rotational to rotational; and rotational to linear. Hence, the configuration of the haptic interface unit may vary, and the configuration of the magnetically-controllable device 26 may vary, depending on: the mechanisms used to resolve the movement of the haptic interface device 26; space constraints; resistance force and/or torque requirements; and cost constraints. Therefore, the teachings of the present invention may be applied to a plurality of different configurations with equal success.

[0071] Referring to **FIG. 3**, one embodiment of the present invention comprises haptic interface unit **55** having a magnetically-controllable device **24** that is adapted to apply resistance forces to haptic interface device **26** through drive mechanism **92**. In **FIG. 3**, the interface device is a steering wheel which is shown for use in **FIG. 1C** in a vehicle. In such an application magnetically controllable device **24** is a rotary brake and monitor **30** displays vehicle operating information. Drive mechanism **92** may be driven by an operator **22** (See **FIG. 1C**.) in operable contact with haptic interface device **26**, such as the steering wheel shown. Sensor **32** is in rotary contact with drive mechanism **92** to determine and report the position of the drive mechanism, which corresponds to the position of haptic interface device **26**. Haptic interface unit **55** further comprises a frame **94** to which magnetically-controllable device **24** and sensor **32** are fixedly mounted, and to which drive mechanism **92** is movably mounted, such as with a low friction element like bearings, bushings, sleeves or the like. The sensor senses rotational displacement of of the steering wheel.

[0072] Drive mechanism **92** comprises a disc **96** fixedly attached to shaft **98**. Disc **96** is configured to engage magnetically-controllable device **24** and sensor **32** during rotation of steering wheel **26**. Disc **96** may comprise a round disc, or only partial segments of a round disc if limited rotation is desired. Disc **96** may comprise peripheral gear teeth as shown or a high-friction surface to engage magnetically-controllable device **24** and sensor **32**.

[0073] Referring to **FIG. 4a**, the magnetically-controllable device **24** of **FIG. 3** is shown in cross section and comprises a pair of first plate members **38** disposed adjacent to both sides of rotating, disc-like second member **40**. Annular ring member **100**, comprising a high magnetic permeability material, forms a peripheral wall around second member **40** and combines with first member **38** to form a housing **99**. Fastening means **102** may be employed in a plurality of places to hold together the components of the magnetically-controllable device **24**. Fastening means **102** may comprises screws, clamps, bonding or any other method for holding together the components of device **24**. Further holding means may fasten the device **24** to the frame **94**.

[0074] An absorbent element **46** which is preferably a disc shaped ring containing magnetically-controllable medium **34** is sandwiched in two places between first member **38** and second member **40**. Magnetic-field generating device **42**, including coil **48** wound about retainer **50** is disposed adjacent first member **38** and second member **40** at the periphery of magnetically-controllable device **24**. The coil **48** is connected by lead wires **53** to the controller **28** (**FIG. 3**). Thus, a magnetic field represented by flux lines **44** is produced upon the energization of magnetic-field generating device **42**.

[0075] Shaft **104** extends through and is fixedly secured to the second member **40** and interconnects at one end to disc **96** (**FIG. 3**) through engaging member **106**, such as a wheel, gear or pinion. Engaging member **106** is fixedly attached to shaft **104**, such as by a force fit, a set screw, a adhesive or welded bond, a pin, and any other suitable method of holding the engaging member in a fixed relationship to the shaft. Engaging member **106** may have peripheral gear teeth or a high friction surface complementary to the periphery of disc **96**. A first bearing member **108** is disposed on shaft **104** between engaging member **106** and second member **40**. First bearing member **108** allows for the rotation of shaft **104** and supports the shaft against radial loads relative to the first member **38**. A suitable bearing member **108** may comprise a roller bearing, a sleeve or washer of a low friction material such as nylon or Teflon®, or other suitable mechanisms. A second bearing member **110** is disposed at the other end of shaft **104**, on the opposing side of second member **40**. Second bearing member **110** provides radial support for shaft **104** and second member **40**. A suitable bearing member **110** may comprise a thrust bearing, a sleeve or washer of a low friction material such as nylon or Teflon®, and other similar mechanisms.

[0076] Disc **96** and engaging member **106** are sized so that the ratio of their diameters is in a range of ratios that allows magnetically-controllable device **24** to provide a suitable amount of resistance force. Similarly, the ratio of the radius of disc **96** and the radius of engaging member **112** fixedly connected to shaft of sensor **32** (**FIG. 3**) similar to engaging member **106**, must be calibrated to insure proper system performance.

[0077] **FIG. 4b** illustrates an alternate embodiment of magnetically controllable device **24b** which may be used in place of the device **24** of **FIG. 4a**. In this device, the shaft **104b** is radially supported in a U-shaped first member **38b** by bearings **108b**, **110b**. Engagement member **106b** engages disc member **96** of **FIG. 3**. The device **24b** attaches to the frame **94** by fastening means **102b** received through the ends of first member **38b** and through spacer **90**. Disc-shaped second member **40** is locked by means of a press fit on shaft **104b** and rotates therewith. Localized absorbent elements **46b** are positioned on either side of second member **40b** and are preferably open celled polyurethane foam adhesively

secured to the insides of first member **38***b*. Magnetically-controllable medium **34***b* is retained by the elements **46***b*. Upon energizing the magnetic field generator **42***b* by providing electrical current to lead wires **53***b* which interconnect to a coil **48** wound about the first member **38**, a magnetic flux **44** is created which is carried by the first member **38***b* and traverses the elements **46***b* retaining the medium **34***b*. This energization changes the rheology of the medium and creates a resistance force that acts to prevent relative rotation between the members **38***b*, **40***b* thereby providing resistance forces to the operator **22**.

[0078] Referring to FIGS. 5-7*b*, another embodiment of the present invention comprises haptic interface unit **155** (control unit and amp not shown for clarity) utilizing a pair of magnetically-controllable devices **24** as described above with reference to **FIG.** 4*a*. **FIG. 1D** illustrates the joystick located in a vehicle where monitor **30** displays operating characteristics of the vehicle. Alternatively, the brakes shown in **FIG.** 4*b* may be used. For clarity, some of the components of device **155** are not shown or shown separately, such as a pair of sensors **32** one of which is shown in **FIG.** 7*b*. In this embodiment, each magnetically-controllable device **24** is adapted to apply resistance forces to haptic interface device **26**, such as a Gravis Pro joystick, through drive mechanism **122**.

[0079] Drive mechanism **122** is in communication with haptic interface device **26** through first **124** and second **126** plates that translate in a y and x direction, respectively, responsive to the movement of the haptic interface device. Each plate **124**, **126** comprises a groove **128** and **130** (**FIG.** 7) within which post **132** at the base of haptic interface device **26** moves. The post **132** is secured to, or integral with, the interface device **26** and moves with the interface device **26** about pivot **125**. The movement of post **132** within the grooves **128**, **130** resolves the motion of haptic interface device **26** into its respective y-direction and x-direction components. Each plate **124**, **126** transfers its linear motion, corresponding to the y or x directions, through first **134** and second **136** wheels, respectively, which are fixedly attached to respective shafts **138**, **140**. As such, the linear motion of plates **124**, **126** is converted to rotational motion in shafts **138**, **140**.

[0080] The rotational motion of shaft **138**, **140** is then provided to each magnetically-controllable device **24** through respective engaging members **106** in contact with respective third **142** and fourth **144** wheels, fixedly attached to shafts **138**,**140**. Further, each shaft **138**, **140** has one end rotatably mounted in housing **146** and the opposite end rotatably mounted in panel **148**. Housing **146** and panel **148** may be manufactured from a variety of materials, such as plastics or metal. Legs **150**, typically provided in four places, fixedly attach housing **146** and panel **148** and provide a base upon which interface unit **155** stands. Thus, the pair of magnetically-controllable devices **24** are able to apply semi-active, variable resistance forces to oppose movement of haptic interface device **26**, such as a joystick, through drive mechanism **122**.

[0081] It should be recognized that the housing **146** and panel **148** are merely exemplary and any suitable housing and support means may be utilized. Further, depending upon the torque achievable in the respective devices **24**, the shafts **138** may be directly attached to devices **24**. Moreover, other types of power transmission or gearing arrangements other than spur gears may be utilized, such as bevel gears, helical gears, worm gears and hypoid gears. Springs (not shown) may be provided that connect between the haptic interface device **26** and the housing **146** to spring bias the device in all directions and provide a return spring function, i.e., center the device.

[0082] Signals representative of the x and y motions are provided by respective sensors **32** including arm **82** received in recesses **84** in the plates **124**, **126**. Movement of the plates **124**, **126** in the respective x and y directions rotates the respective arms **84** of sensors **32**, which are preferably rotary potentiometers. This produces a signal corresponding to x and y motion which is processed by the control system to provide force feedback signal to the respective device **24**. The one or more buttons or triggers **79***a*, **79***b* shown send additional signals to the control unit **54** (**FIG. 1**).

[0083] **FIG. 8** illustrates another embodiment of haptic interface unit **255** with the cover portion of housing removed for clarity. The unit **255** comprises a haptic interface device **26** pivotally moveable to cause movements in the respective x and y directions or any combination thereof. Such movements of the device **26** cause respective movements in rack and pinion assemblies **86***x*, **86***y*. interconnected to respective magnetically controllable devices **24***x*, **24***y*. Assemblies **86***x*, **86***y* include a rack **87** and pinion **106**. The rack **87** includes projections **91** which slide in slots **89** formed in the housing portion **246** thereby restricting motion to only along the z direction. A spherical ball **93** mounted on extension **83** is received in guide **95** formed in the haptic interface device **26**.

[0084] Movement of the device **26** in the x direction, for example, pivots the device below flange **97** about a pivot point (not shown) and causes guide **95** to engage ball **93** to move rack **87***x* in the z direction. Likewise, movement of device **26** in the y direction causes guide **95** to engage ball **93** and move rack **87***y* in the z direction. Any z movements of racks **87***x*, **87***y* cause teeth **85** on the outer surface of racks **87***x*, **87***y* to engage teeth on pinions **106***x*, **106***y*. This rotates respective shaft **104***x*, **104***y* (not shown) and fixedly secured second members **40***x*, **40***y* of magnetically controllable devices **24***x*, **24***y*.

[0085] Sensors **32***x*, **32***y* generate signals representative of the x and y movements through utilizing rack assemblies similar to that described in **FIG.** 8*b* where a moving component of sensor **32***x*, **32***y* is interconnected to the rack (e.g. **87***s*). Coils **48***x*, **48***y* are selectively energized to produce a magnetic flux in U-shaped first members **38***x* whose legs straddle the second member **40***x*, **40***y*. A magnetically controlled medium (not shown) is included between the respective legs and the second member **40***x*, **40***y* as shown in **FIG.** 4*b* and is preferably retained in an absorbent member as described therein. The control system **28** in response to position signals from leads **53***x*', **53***y*' controls the effective resistance generated by devices **24***x*, **24***y* by supplying signals to leads **53***x*, **53***y*.

[0086] Referring to **FIGS. 9 and 10**, another embodiment of a magnetically-controllable device **24** comprises a first member **38** having a u-shaped body that receives second member **40** at its open end **160**. An absorbent element **46** is disposed in each working space **36** between first member **38** and second member **40**. Each absorbent element **46** contains magnetically-controllable medium **34**. Magnetic-field generating device **42** is disposed about closed end **162** of second member **40**, and creates a magnetic field through magnetically-controllable medium **34**, as represented by flux lines **44**, upon energization by controller **28** (**FIG. 1**). Magnetic-field generating device **42** is connected to controller **28** by

wires **53**. As indicated by the arrows on second member **40** (**FIG. 9**), the relative movement between the second member and first member **38** may be linear, rotational or curvilinear. Thus, this embodiment of magnetically-controllable device **24** provides resistance forces to oppose linear, rotational or curvilinear relative movements between first member **38** and second member **40**.

[0087] The magnetically-controllable device **24** in **FIGS. 9 and 10** may be integrated into haptic interface unit **55** (**FIG. 3**), by mounting the device to frame **94** and having disc **96** act as second member **40** much the same as is shown in **FIG. 4*b***. In this case, disc **96** needs to comprise a magnetically soft material, as discussed above in reference to second member **40**. Similarly, a pair of devices, like the magnetically-controllable device **24** in **FIGS. 9 and 10**, may be integrated into haptic interface unit **155** (FIGS. *5-7b*). This may be accomplished in a joystick, for example, by mounting the devices to housing **146** and having first and second translating plates **124** and **126** act as a second member **40** in each device. Of course, plates would need to be manufactured from a magnetically permeable material.

[0088] Finally, referring to **FIG. 11**, another embodiment of magnetically-controllable device **24** comprises first member **38**, having a curved, annular ring-shaped body, and second member **40** having a pivotable, disc-like body. Magnetic-field generating device **42** is an annular shaped member at the periphery of second member **40**, adjacent to first member **38**. Magnetically-controllable medium **34** is included in a chamber **35** and in the working space **36** between first member **38** and second member **40**. Magnetic-field generating device **42** creates a magnetic field through magnetically-controllable medium **34** in working space **36**, as represented by flux lines **44**, upon energization by controller **28** (not shown). Magnetic-field generating device **42** is connected to controller **28** by wires **53**.

[0089] An operator **22** (**FIG. 1D**) in operable contact with haptic interface device **26**, such as a joystick, moves second member **40** fixedly attached shaft haptic interface device **26**. Pivot member **172** opposes device **26** on the other side of second member **40**. Pivot member **172** preferably comprises a post having a ball-shaped end. Pivot member **172** is secured to magnetically-controllable device **24** by bottom plate **174**, which also is fixedly attached to first member **38**. Similarly, top member **176** may be connected to first member **38** to further reinforce magnetically-controllable device **24**. Thus, as one skilled in the art will recognize, the teachings of the present invention may be implemented in a variety of haptic interface units to provide resistance forces to oppose the motion of haptic interface device **26** in haptic interface system **20**. Moreover, it will be recognized that a wide variety of magnetically controllable devices may be utilized herein. For example, the magnetorheological fluid devices described in commonly assigned U.S. Pat. Nos. 5,816,372, 5,711,746, 5,652,704, 5,492,312, 5,284,330 and 5,277,281 may be used.

[0090] Although the invention has been described with reference to these preferred embodiments, other embodiments can achieve the same results. Variations and modifications of the present invention will be apparent to one skilled in the art and the following claims are intended to cover all such modifications and equivalents.

What is claimed is:

1. A haptic interface system comprising:

a haptic interface device movable by an operator in at least one direction of displacement, the haptic interface system providing resistance forces to the haptic interface device;

a controller for receiving a variable input signal and providing a variable output signal, said controller adapted for running a program that processes said variable input signal and in response derives said variable output signal; and

a magnetically-controllable device that receives said variable output signal and provides said variable resistance force in proportion to said variable output signal, said magnetically controllable device comprising a volume of a magnetically controllable medium, the variable resistance forces being provided by changing the rheology of the magnetically controllable medium in response to said output signal to thereby directly control the ease of movement of the haptic interface device, said variable resistance forces being provided to resist displacement of the haptic interface device by the operator in at least one direction of displacement of said device.

2. The haptic interface system as recited in claim 1, wherein said haptic interface device comprises a steering device.

3. The haptic interface system as recited in claim 2 wherein said steering device is for steering a vehicle or machine.

4. The haptic interface system as recited in claim 1, wherein said haptic interface device comprises a joystick.

5. The haptic interface system as recited in claim 2, wherein said haptic interface device comprises a steering wheel.

6. The haptic interface device as claimed in claim 2 wherein the steering device is a steering yoke.

7. The haptic interface system as claimed in claim 1 wherein said haptic interface device comprises a lever.

8. The haptic interface system as claimed in claim 1 wherein the magnetically controllable medium is magnetorheological powder.

10. The haptic interface system as recited in claim 1, wherein said magnetically-controllable device comprises:

a magnetic-field generating device energizable by said variable output signal to provide a variable strength magnetic field;

a first member adjacent to said magnetic field generating device;

a second member adjacent to said magnetic field generating device and connected to said haptic interface device; and

wherein said magnetically-controllable medium is located between said first member and said second member.

11. A haptic interface system as recited in claim 10, further comprising an absorbent element disposed between said first member and said second member, said absorbent element containing said magnetically-controllable medium.

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